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FLOODING STRESS

Sugarcane Response to Nitrogen Fertilization on a Histosol with Shallow Water Table and Periodic Flooding

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Abstract

Sugarcane (*Saccharum* spp.) is increasingly exposed to periodic floods and shallow water tables on Histosols in Florida's Everglades Agricultural Area (EAA). In the past, when these soils were usually well drained, they provided excess N for sugarcane through microbial oxidation. It is not known if supplemental N would now improve yields because microbial oxidation is reduced by shallow water tables and periodic floods. The purpose of this study was to evaluate the effects of N fertilizer rates on two sugarcane cultivars exposed to a 25-cm water-table depth with and without repeated 2-day floods. Two studies were planted in containers in 2001 and 2002 with two sugarcane cultivars and five equally spaced rates of N fertilizer from 0 to 200 kg ha^{-1}. Leaf, stalk and root weights were reduced by periodic flooding and the magnitude of the reduction sometimes differed between cultivars. Plant weights, leaf chlorophyll content (SPAD) and leaf N content were often highest near an N rate of 100 kg ha^{-1}. Usually, N fertilizer rate did not interact with water treatment. Nitrogen fertilization may be useful for sugarcane exposed to water-table depths of 25 cm with and without 2-day repeated floods on EAA Histosols.

Introduction

The Everglades Agricultural Area (EAA) is a 280 000-ha basin of Histosols that lie on a limestone bedrock in the northern region of the Everglades in Florida. Sugarcane is grown on about 163 000 ha in the EAA (Glaz 2007). Prior to the construction of an extensive public/private system of canals through the northern Everglades, the EAA was flooded most of the time (Snyder and Davidson 1994). Until recently, farmers used the canal system to effectively manage desired water-table depths of 40–95 cm in sugarcane fields (Omary and Izuno 1995).

The canal system still helps to control water tables in EAA sugarcane fields. However, it is now common for sugarcane to be exposed to high water tables and periodic floods in all crop-growth cycles. Three major reasons for the increased occurrence of shallow water tables are: (i) increased soil compaction resulting from agricultural operations; water tables on EAA Histosols rise about 10 cm for each centimetre of rainfall; (ii) there has been a long-term loss of soil depth because of soil subsidence; and (iii) growers practice voluntary and regulated pumping restrictions that control P discharge from the EAA. These factors were described previously in a more detailed manner (Glaz et al. 2004).

In a lysimeter study, Glaz et al. (2004) reported substantial yield losses attributable to periodic floods of 1-week duration for CP 95-1376, a genotype that did not form constitutive stalk aerenchyma. Yields of a second genotype that formed constitutive aerenchyma, CP 95-1429, were not affected by periodic flooding. In a follow-up study, Glaz and Gilbert (2006) found that yields were moderately improved by periodic floods of 2-day duration applied every 2 weeks. Gilbert et al. (2008) reported substantial yield losses of sugarcane which is exposed to 3-month floods applied during the summer growing seasons. The largest yield losses occurred in the ratoon crops. Therefore, they proposed that research into flood tolerance of sugarcane in the EAA should focus on short-duration periodic flooding.

Sugarcane and rice (*Oryza sativa* L.) are the two crops in the EAA that produce well under the current shallow water-table depths and periodic flooding characteristic of the EAA. Henshaw et al. (2007) reported that growth and biomass of soya bean (*Glycine max* L. Merr.) were reduced in the EAA by flood durations of 2 or 4 weeks, applied 21 days after sowing.

Under routine growth conditions, it is assumed that microbial oxidation of organic soils in the EAA made excessive N available to sugarcane. The annual rate of soil loss in the EAA because of microbial oxidation was last measured at 1.3 cm (Shih et al. 1998). Terry (1980) estimated that 686 kg N ha^{-1} is mineralized for each centimetre of EAA soil lost to microbial oxidation. Thus, about 892 kg N ha^{-1} was mineralized annually with an annual soil loss rate of 1.3 cm.

Coale et al. (1993) estimated annual N accumulation by a sugarcane crop on Florida Histosols at 142 kg ha^{-1}, well below the estimated 892 kg ha^{-1} that is potentially mineralized. However, the recent findings by Morris et al. (2004) that microbial oxidation differed at water-table depths of 33 and 50 cm and was controlled by periodic floods and drainage to a depth of 16 cm raises the questions whether the intervals of flood and drainage to shallow depths in EAA fields as well as constant shallow water-table depths may result in periods of insufficient N availability for optimum sugarcane yields. Adding to this concern was the report by Cisar et al. (1992) that visual quality and clipping yield of St. Augustinegrass [*Stenotaphrum secundatum* (Walt.) Kuntze] grown on an EAA Histosol at a water-table depth of 30 cm were improved by bi-monthly applications of 50 kg N ha^{-1}. However, Glaz and Gilbert (2006) reported that repeated foliar applications of N at rates of 0.0 and 5.6 kg ha^{-1} did not affect yields of sugarcane growing at different water-table depths and with 2-day periodic floods.

As reported by Wiedenfeld and Enciso (2008), there is a lack of information on how sugarcane responds to N fertilization when soil moisture is above or below optimum levels. Wiedenfeld (1995) reported that sugarcane did not respond to N fertilization when water was limited, but Wiedenfeld and Enciso (2008) reported that positive linear responses from 0 to 180 kg ha^{-1} of N were not affected by irrigation level.

Farmers in the EAA must sustain low levels of P discharge to comply with the efforts to restore the Everglades. Movement of phosphorus from farms in the EAA is decreased by reducing the quantity and rate of water discharged from farms to public canals (Sievers et al. 2003). The principle of many strategies that achieve reductions in phosphorous discharge from the EAA is to allow water tables to drop more by evapotranspiration and less by pumping to public canals (Daroub et al. 2004). This results in repeated short-duration floods on sugarcane growing in the EAA.

Because integrative information on periodic flooding and cultivar response to soil applied N fertilizer is lacking, the current investigation was undertaken. The purpose of this pot study was to evaluate the effects of soil-applied N fertilizer rates on two sugarcane cultivars exposed to a 25-cm water-table depth with and without repeated 2-day floods.

Materials and Methods

Eighty 38-L pots (top diameter = 37 cm, bottom diameter = 32 cm, and height = 38 cm) were filled with 36 cm of organic soil typical of the EAA (Euic, hyperthermic Lithic Haplosaprist). Pots were flooded and drained and additional soil was subsequently added to achieve a soil depth of 36 cm in each pot. All water applied to pots in these experiments was ground water. Each pot was placed outdoors in a plastic container (length = 58 cm, width = 45 cm, height = 54 cm). One recently emerged plant of sugarcane cultivar, CP 80-1743 (Deren et al. 1991), was transplanted into 40 pots and one recently emerged plant of LCP 85-384 (Milligan et al. 1994) was transplanted into 40 pots on 1 October 2001 (Experiment 1) and 21 March 2002 (Experiment 2). A new set of pots was filled with soil as described in Experiment 1 and used for Experiment 2. Water-table depth was maintained at 13 cm until 10 October 2001 and 9 April 2002 in Experiments 1 and 2, respectively, when water-table depths were dropped to 25 cm in each experiment. The planting date of Experiment 1 coincided with the normal sugarcane planting cycle in Florida and the planting date of Experiment 2 coincided with the ratoon regrowth that occurs after harvesting of sugarcane in Florida. Experiment 1 was conducted for 19 weeks and Experiment 2 was conducted for 11 weeks. Sugarcane growth in Florida is considerably faster during the months when Experiment 2 was conducted compared with Experiment 1.

CP 80-1743 had been the most widely planted sugarcane cultivar in Florida for several years. At the time of these plantings (Glaz and Vonderwell 2003), and among nine sugarcane cultivars in Florida, CP 80-1743 was identified as the least tolerant to high water tables (Glaz et al. 2002). The yield loss of CP 80-1743 at a summer water-table depth of ≤ 15 cm was 25 % compared with its yield at a water-table depth maintained between 15 and 33 cm. The mean yield loss, because of shallow water-table depth, of all nine cultivars in that experiment was 8.3 %. Thus, CP 80-1743 represented a sugarcane cultivar that was selected under conditions of high N availability and shallow water-table conditions characteristic of the EAA, but had relatively poor tolerance to these shallow water-tables compared with other Florida cultivars. LCP 85-384 was selected for Louisiana rather than for the organic soils of the EAA with their high N availability. While these experiments were conducted, LCP 85-384 was the most widely planted cultivar in Louisiana (Legendre and Gravois 2003). LCP 85-384 represented a cultivar that was not selected under unusual N fertility or under shallow water-table depths.

Based on bulk soil tests, nutrients were applied to the soil surface near the planted stalk sections, at rates of 25 and 139 kg ha^{-1} of P and K, respectively, and at rates of 0.1, 0.1, 0.7, 0.3, 0.1 and 0.3 kg ha^{-1} of B, Cu, Fe, Mn, Mo and Zn, respectively. Fertilizer rates were as recommended by Sanchez (1990) for sugarcane and were calculated based on the soil surface area in the pots.

Each experiment was planted as a complete factorial in a randomized complete block design with four replications. Treatments included CP 80-1743 and LCP 85-384 (two cultivars), two water-table treatments and five rates of N fertilizer. Water-table treatments were a constant water-table depth of 25 cm and 2-day flooding each week followed by drainage to a depth of 25 cm for 5 days. Water-table depths were maintained at nearly 25 cm by replacing water lost because of evapotranspiration on Mondays, Wednesdays and Fridays. This water was added by hose to the soil surface. Flooding was initiated on 5 November 2001 in Experiment 1 when the mean plant height was 14 cm, and on 9 April 2002 in Experiment 2 when the mean plant height was 8 cm. Plant height was measured from the soil surface to the top visible dewlap. Van Dillewijn (1952) described the dewlap in sugarcane as the junction between the leaf blade and the leaf sheath. There were 14 periodic floods applied in Experiment 1 and 11 periodic floods applied in Experiment 2. Rates of N fertilizer, applied as urea, were 0, 50, 100, 150 and 200 kg N ha^{-1}. All N fertilizer was broadcast on the soil surface after transplanting.

A Minolta Chlorophyll Meter, SPAD-502 (Spectrum Technologies Inc.; Plainfield, IL, USA), was used to estimate leaf chlorophyll content. Three SPAD measurements per pot were taken on the leaf above the top visible dewlap, the leaf at the top visible dewlap, and the leaf below the top visible dewlap. The mean SPAD of these three leaves is reported. Leaves from the largest tiller in each pot were measured for SPAD, using material on the abaxial side of the leaf away from the midrib. In Experiment 1, SPAD was measured in 2001 on 7 November, 21 November and 19 December. In Experiment 2, SPAD was measured on 23 April 2002.

The leaves at and immediately below the top visible dewlap from the largest plant in each pot were separated at harvest to determine leaf N content. Tissue samples were dried in a forced draft oven at 51 °C until no change in weight was observed. The samples of leaves, including midribs, were ground to pass through a 2 mm sieve. Nitrogen was determined from 2 mg of dried leaf tissue using a PerkinElmer CHNS Analyzer (PerkinElmer Inc., Waltham, MA, USA) by combustion in pure oxygen to N_2 (Patterson 1973). Nitrogen gas was determined as a function of its thermal conductivity and reported in microgram nitrogen per gram (μg N g^{-1}) leaf tissue.

Experiments 1 and 2 were harvested on 14 February 2002 and 24 June 2002, respectively. On each harvest date, all tillers were cut as near to the soil surface as possible. Fresh weights of leaves and stalks were measured for each pot on the day of harvest. During the week after harvesting Experiment 2, roots were separated from the soil and fresh root weight was measured. Harvested stalks, leaves and roots were placed in an oven set at 63 °C and dry weights were recorded until no change in weight was observed.

In both experiments, treatments were replicated four times in randomized complete block designs. All statistical analyses were performed using PROC MIXED (SAS, 2003). Effects of treatments on SPAD in Experiment 1 were analysed as randomized complete block designs with measurement day as repeated measures. Based on procedures described by Tao et al. (2002) and information provided by Littell et al. (1996), the compound symmetry covariance structure was used to describe repeated measures covariance. To analyse the combined effect of experiments on SPAD, only the 21 November 2001 measurement day from Experiment 1 was used because Experiment 2 had only one measurement day for SPAD.

Significant effects involving N fertilizer rate identified by analyses of variance were further analysed by linear or quadratic regression. Regressions were calculated using least square means. To identify differences among cultivar or water treatment means, LSD was used. Differences were identified as significant at $P \le 0.10$ and as highly significant at $P \le 0.01$. Probability levels are noted in parentheses when $P > 0.05$.

Results and Discussion

Leaf weight

Cultivar, water treatment and N had highly significant effects on leaf weight for the data combined over both experiments (Table 1). However, because all three of these main effects had highly significant interactions with experiment, effects of cultivar, water treatment and N on leaf weight will be discussed separately for each experiment.

In Experiment 1, cultivar differences were highly significant for leaf weight and cultivar was not involved in any

Table 1 Probabilities of *F*-values of fixed effects for leaf and stalk weights and leaf chlorophyll content of sugarcane cultivars CP 80-1743 and LCP 85-384 exposed to two water-table treatments and five N rates in two combined experiments

Fixed effect	Dry weight: Leaf	Dry weight: Stalk	Leaf chlorophyll content (SPAD)
Cultivar (C)	<0.01***	<0.01***	<0.01***
Water (W)	<0.01***	<0.01***	<0.03**
C × W	0.06*	<0.01***	0.70
N fertilizer (N)	<0.01***	0.04**	0.06*
N linear (N_L)	0.51	0.79	0.50
N quadratic (N_q)	<0.01***	<0.01***	<0.01***
C × N	0.31	0.19	0.85
C × N_L	0.08*	0.02**	0.92
C × N_q	0.91	0.86	0.61
W × N	0.81	0.87	0.01***
W × N_L	0.91	0.61	<0.01***
W × N_q	0.35	0.48	0.09*
C × W × N	0.22	0.41	0.75
Experiment (E)	<0.01***	<0.01***	0.11
E × C	<0.01***	<0.01***	0.88
E × W	<0.01***	<0.01***	0.33
E × C × W	<0.01***	<0.01***	0.01***
E × N	<0.01***	<0.01***	0.06*
E × N_L	<0.01***	<0.01***	0.01***
E × N_q	0.03**	0.02**	0.55
E × C × N	0.33	0.46	0.27
E × W × N	0.53	0.64	0.93
E × C × W × N	0.22	0.42	0.89

*, ** and ***Significant at the 0.10, 0.05 and 0.01 probability levels, respectively.

significant interactions (Table 2). CP 80-1743 had a significantly higher leaf weight than LCP 85-384 (Table 3). Leaf weight of the drained treatment was significantly higher than that of the flooded treatment and this difference was not affected by interactions with other effects. Thus, periodic flooding reduced leaf weight of both cultivars similarly in the first experiment.

In Experiment 2, cultivar and water differences were highly significant, but the cultivar × water treatment interaction was also highly significant (Table 2). This interaction was significant because the leaf weight of LCP 85-384 was significantly higher than that of CP 80-1743 in the drained treatment, but the leaf weights of the two cultivars did not differ in the flooded treatment (Table 3). This suggests that the 2-day periodic flooding was more detrimental to LCP 85-384 than to CP 80-1743 in the second experiment. CP 80-1743 was identified as the least tolerant of shallow water-table depth among nine Florida sugarcane cultivars (Glaz et al. 2002). That CP 80-1743 was less negatively affected by the 2-day floods than LCP 85-384 suggests that sugarcane genotype selection in the CP programme in Florida has included some degree of exposure to flood, although this character is not routinely evaluated. The higher leaf weight for LCP 85-384 in Experiment 2 suggests that this cultivar, which was selected for Louisiana, was more adapted to the cooler conditions during the early weeks of Experiment 2 than CP 80-1743.

Nitrogen significantly affected leaf weight in each experiment (Table 2), but combined across experiments, the cultivar × N interaction was significant (P = 0.08) for leaf weight regressed linearly on N fertilizer rate

Table 2 Probabilities of F values, by experiment, of fixed effects for leaf, stalk, and root dry weights (wt) of sugarcane cultivars CP 80-1743 and LCP 85-384 exposed to two water-table treatments and five N fertilizer rates

Fixed effect	Experiment 1: Leaf wt	Experiment 1: Stalk wt	Experiment 2: Leaf wt	Experiment 2: Stalk wt	Experiment 2: Root wt	Experiment 2: Leaf N content
Cultivar (C)	<0.01***	0.03**	<0.01***	<0.01***	0.02**	0.21
Water (W)	<0.01***	0.02**	<0.01***	<0.01***	<0.01***	0.49
C × W	0.22	0.18	0.01***	<0.01***	0.14	0.09*
Nitrogen (N)	<0.01***	<0.01***	0.02**	0.02**	<0.01***	0.09*
N linear (N_L)	<0.01***	<0.01***	0.16	0.07*	0.05**	0.45
N quadratic (N_q)	0.08*	0.23	<0.01***	0.01***	<0.01***	0.05**
C × N	0.79	0.70	0.29	0.29	0.80	0.48
C × N_L	0.34	0.21	0.13	0.05**	0.28	0.62
C × N_q	0.64	0.61	0.73	0.98	0.89	0.51
W × N	0.35	0.78	0.75	0.76	0.34	0.13
W × N_L	0.12	0.38	0.55	0.39	0.24	0.78
W × N_q	0.96	0.57	0.31	0.35	0.10*	0.51
C × W × N	0.99	0.91	0.16	0.37	0.21	0.66
C × W × N_L	0.94	0.45	0.55	0.43	0.66	0.94
C × W × N_q	0.97	0.94	0.29	0.32	0.06*	0.46

*, ** and ***Significant at the 0.10, 0.05, and 0.01 probability levels, respectively.

Table 3 Dry weights of two sugarcane cultivars, two water treatments, and their interactions averaged over five N fertilizer rates in two experiments

		Experiment 1 (grams per pot)		Experiment 2 (grams per pot)		
Cultivar	Water	Leaf	Stalk	Leaf	Stalk	Root
CP 80-1743	Mean	70.7	29.5	106.5	64.1	38.6
LCP 85-384	Mean	57.6	24.7	145.1	99.4	43.0
P > *t*		<0.01	0.03	<0.01	<0.01	0.02
Mean	Drain	72.8	29.7	171.0	105.4	46.3
Mean	Flood	55.5	24.5	80.6	58.0	35.4
P > *t*		<0.01	0.02	<0.01	<0.01	<0.01
CP 80-1743	Drain	81.8	33.6	140.5	78.3	42.7
CP 80-1743	Flood	59.7	25.4	72.4	49.9	34.5
LCP 85-384	Drain	63.9	25.8	201.5	132.6	49.9
LCP 85-384	Flood	51.3	23.5	88.8	66.1	36.2
LSD (0.05)		10.9	6.1	23.4	16.0	5.1

(Table 1). Although the linear response of each cultivar combined across experiments was not significantly affected by N rate, the trends were for LCP 85-384 leaf weight to decline with increasing N fertilizer rates and for CP 80-1743 leaf weights to increase (Fig. 1a). In Experiment 1, the mean leaf weight of the two cultivars significantly increased at the rate of 0.13 g kg^{-1} ha^{-1} increase in N fertilizer rate (Fig. 2a). In Experiment 2, the mean leaf weight of both cultivars had a quadratic response to N fertilizer rate (Table 2 and Fig. 2a). The maximum predicted mean leaf weight of the two cultivars occurred at the N fertilizer rate of 86 kg ha^{-1}. Because our N fertilizer source was urea, some N may have been lost because of volatilization. Comparisons among treatments probably were not affected by the volatilization. However, with a different source of N fertilizer, responses reported in this study might have occurred at lower N rates.

One of the objectives of this study was to determine if supplemental N fertilization would increase growth under periodic flooding. Water treatment did not affect the significant responses in leaf weight to N fertilizer rate. However, overall, leaf weights of both water treatments responded positively to increasing N rates. These results for leaf weight suggest that the constant 25-cm water-table depth and the periodic flooding similarly reduced N made available through microbial oxidation. Thus, it can be inferred that supplemental N fertilizer may increase leaf growth under water regimes similar to those used in this study. This result is supported by the finding of Cisar et al. (1992) that visual quality and clipping yield of St. Augustinegrass grown on an EAA Histosol at a water-table depth of 30 cm were improved by bimonthly applications of 50 kg N ha^{-1}.

Root weight

Root weights were measured only in Experiment 2, and cultivar, water and N all significantly affected root weight. However, the three-way interaction that measured the quadratic response to N for the cultivar × water interaction was also significant (P = 0.06) (Table 2). Looking only at the main effects of cultivar and water treatment, LCP 85-384 had higher root weight than CP 80-1743 and the mean root weight of each cultivar was higher under drain than flood (Table 3).

Adding the effect of N modifies these results moderately. The highly significant quadratic response to N fertilizer

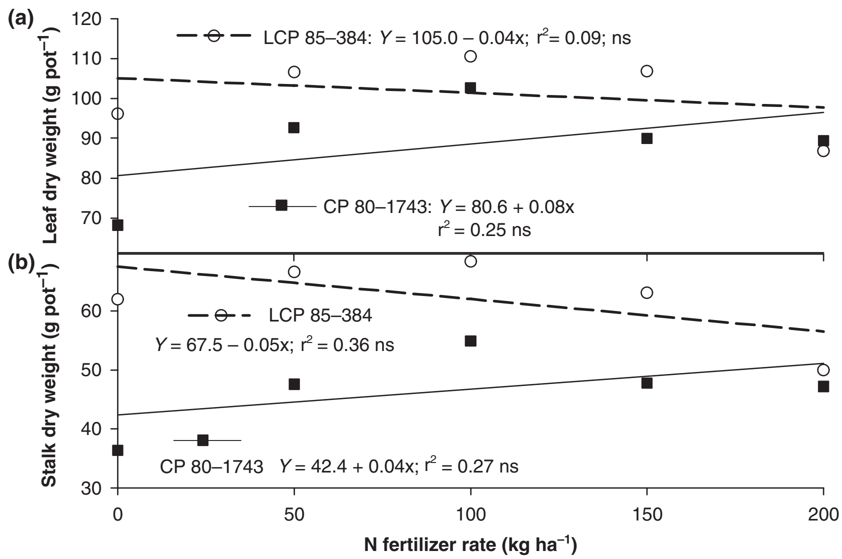

Fig. 1 Effect of N fertilizer rate on leaf (a) and stalk (b) weights of CP 80-1743 and LCP 85-384 combined over two experiments.

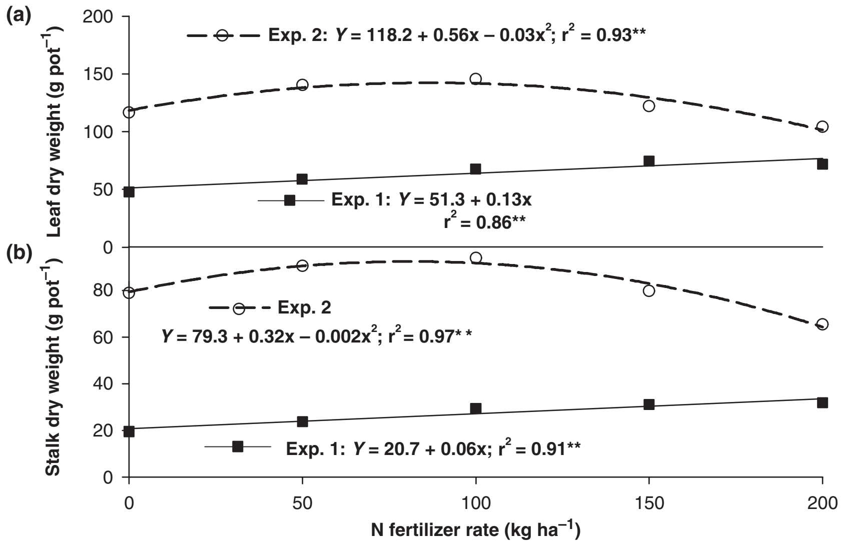

Fig. 2 Responses of sugarcane leaf (a) and stalk (b) dry weights to N fertilizer rate in two pot experiments.

rate of the roots of LCP 85-384 under continuous drainage indicates that the drained LCP 85-384 root weight was significantly greater than that of CP 80-1743 under drainage between N rates of about 50 and 150 kg ha^{-1} (Fig. 3). Maximum predicted root weight of LCP 85-384 under drainage occurred at the N fertilizer rate of 90 kg ha^{-1}. Moreover, weights of the flooded roots of the two cultivars were similar to each other at all N rates, but the flooded CP 80-1743 root weight had a significant quadratic response to N rate and root weights of LCP 85-384 under flood were similar across N rates. Maximum predicted root weight of CP 80-1743 under flood occurred at the N fertilizer rate of 110 kg ha^{-1}. Thus, in contrast to the conclusions reached regarding leaf response to N and flood, CP 80-1743 root weight under flood improved with N fertilizer rates up to 110 kg ha^{-1}. LCP 85-384 root weights under drainage responded positively to N fertilizer rates up to 90 kg ha^{-1}, but the periodically flooded roots of LCP 85-384 did not respond to N fertilizer.

Relative leaf chlorophyll content (SPAD) and leaf N content

Cultivar, water and N all significantly affected SPAD, and all were involved in significant interactions with experi-

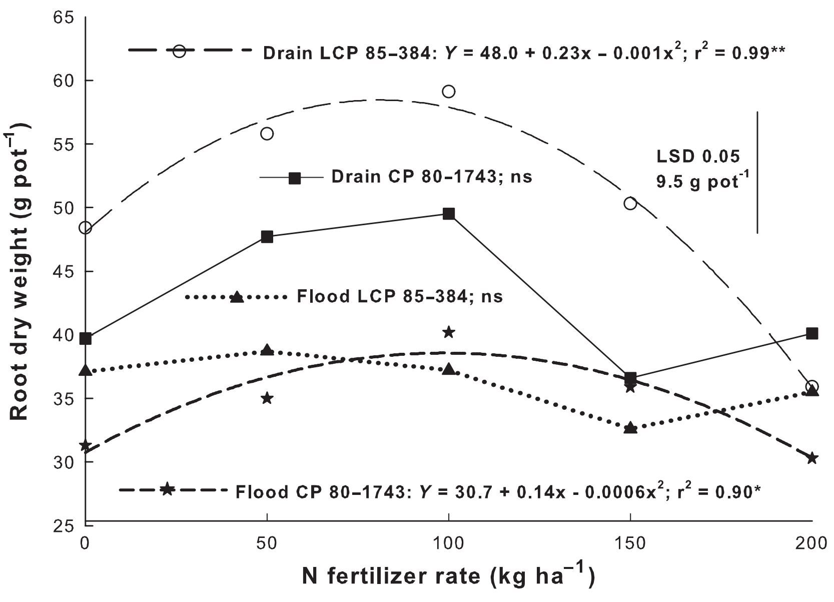

Fig. 3 Root weight responses of two sugarcane cultivars exposed to repeated 2-day floods or continuous drainage to five rates of N fertilizer in Experiment 2.

Table 4 Probabilities of *F*-values of fixed effects for relative leaf chlorophyll content (SPAD) of sugarcane cultivars CP 80-1743 and LCP 85-384 exposed to two water-table treatments and five N fertilizer rates

	Experiment 1				Experiment 2
Fixed effect	Days combined	Day 1	Day 2	Day 3	Day 1
Cultivar (C)	<0.01***	<0.01***	<0.01***	0.31	<0.01
Water (W)	0.10*	0.40	0.07*	0.33	0.26
C × W	0.13	0.83	0.31	0.06*	0.05**
Nitrogen (N)	0.09*	0.06*	0.06*	0.21	<0.01***
N linear (N_L)	0.51	0.20	0.31	0.14	<0.01**
N quadratic (N_q)	0.02**	0.02**	0.02**	0.40	0.04**
C × N	0.69	0.42	0.60	0.31	0.46
C × N_L	0.32	0.21	0.38	0.88	0.08*
C × N_q	0.84	0.62	0.21	0.83	0.97
W × N	0.50	0.38	0.59	0.93	0.10*
W × N_L	0.24	0.40	0.24	0.53	0.03**
W × N_q	0.26	0.19	0.38	0.66	0.20
C × W × N	0.81	0.36	0.73	0.93	0.35
C × W × N_L	0.27	0.05**	0.19	0.55	0.69
C × W × N_q	0.83	0.87	0.61	0.90	0.42
Day (D)	<0.01***	–	–	–	–
D × C	<0.01***	–	–	–	–
D × W	0.65	–	–	–	–
D × C × W	0.26	–	–	–	–
D × N	0.07*	–	–	–	–
D1 vs. D2 × N_L	0.07*	–	–	–	–
D1 vs. D2 × N_q	0.90	–	–	–	–
D1 vs. D3 × N_L	0.02**	–	–	–	–
D1 vs. D3 × N_q	0.25	–	–	–	–
D × C × N	0.20	–	–	–	–
D × W × N	0.97	–	–	–	–
D × C × W × N	0.66	–	–	–	–

*, ** and ***Significant at the 0.10, 0.05 and 0.01 probability levels, respectively.

ments (Table 1). For the mean of all 3 days on which SPAD was measured in Experiment 1, continuous drainage resulted in higher SPAD than 2-day periodic flooding (P = 0.10) (Tables 4 and 5).

Cultivar affected SPAD significantly in both experiments (Table 4). However, SPAD was measured on 3 days in the first experiment and cultivar interacted significantly with day. On the first two measurement days, SPAD of LCP 85-384 was significantly higher than that of CP 80-1743 (Table 5). On the final measurement day in Experiment 1, the two cultivars had similar SPAD levels. This suggests that to identify differences in SPAD among cultivars, measurements should be taken early. In Experiment 2, cultivar interacted significantly with water treatment (Table 4). In this experiment, the continuously drained LCP 85-384 had higher SPAD than the periodically flooded LCP 85-384 and both the drained and flooded treatments of CP 80-1743, and water treatment did not affect CP 80-1743 SPAD (Table 5). The similarity in SPAD for CP 80-1743 under both water treatments suggests that CP 80-1743 is more tolerant of flooding than LCP 85-384. Furthermore, that water treatment significantly affected the SPAD of one of two cultivars suggests that SPAD may be a useful tool for differentiating flood tolerance among genotypes.

Nitrogen fertilizer rate significantly affected SPAD in each experiment and these effects differed by measurement day in Experiment 1. On the first two measurement days, SPAD had similar quadratic responses to N fertilizer rate (Fig. 4). On the first measurement day, maximum SPAD was predicted at 84 kg ha^{-1} of N fertilizer, and on day 2 maximum SPAD was predicted at 113 kg ha^{-1} of N fertilizer. These significant responses of SPAD to N fertilizer on the first two measurement days compared with the non-significant response on the third measurement day reinforce the conclusion with cultivar SPAD responses that differences in SPAD will more likely be detected at earlier stages of growth.

Response of SPAD was not affected by N fertilizer rate interactions with cultivar or water treatment. The cultivar × water treatment interaction for leaf N content was significant in Experiment 2 (P = 0.09) (Table 2). The probable cause of this interaction was that, under the continuously drained treatment, the leaf N content

Table 5 Mean relative chlorophyll content (SPAD) of the top three leaves of two sugarcane cultivars exposed to two water treatments measured on three days in Experiment 1 and one day in Experiment 2, and leaf N content measured on one day in Experiment 1

Experiment	Cultivar	Water treatment	Day	SPAD	Leaf N content g kg^{-1}
1	CP 80-1743	Mean	1	40.5	–
1	LCP 85-384	Mean	1	45.5	–
1	P > *t*	Mean	1	<0.01**	–
1	CP 80-1743	Mean	2	38.1	–
1	LCP 85-384	Mean	2	42.8	–
1	P > *t*	Mean	2	<0.01**	–
1	CP 80-1743	Mean	3	37.3	1.09
1	LCP 85-384	Mean	3	38.4	1.17
1	P > *t*	Mean	3	0.31	0.21
1	Mean	Drain	Mean	41.1	1.15
1	Mean	Flood	Mean	39.8	1.11
1	Mean	P > *t*	Mean	0.10*	0.49
2	CP 80-1743	Drain	1	36.5	1.06
2	LCP 85-384	Drain	1	43.1	1.25
2	CP 80-1743	Flood	1	37.3	1.13
2	LCP 85-384	Flood	1	40.2	1.10
2	LSD (0.05)			2.5	0.17

* and **Significant at the 0.10 and 0.01 probability levels, respectively.

of LCP 85-384 was higher than that of CP 80-1743, whereas, the leaf N contents of both cultivars were similar under periodic flood (Table 5). Leaf N content also had a significant quadratic response to N fertilizer rate (Table 2). For this quadratic response, the predicted maximum leaf N content occurred at the N fertilizer rate of 110 kg ha^{-1} (Fig. 5). This N fertilizer rate was similar to those identified for predicted maximum SPAD and root weight. The declines in leaf N content, SPAD and root weight at N rates higher than approximately 100 kg ha^{-1} suggest that these N rates were detrimental to sugarcane growing in the shallow water-table depths used in this study. This supports the concern raised by Wiedenfeld and Enciso (2008) that more information is needed on sugarcane's response to N fertilization when subjected to above- or below-optimum soil moisture levels.

In Experiment 2, the linear SPAD responses of the two cultivars to N fertilizer rate differed (Table 4). The SPAD of LCP 85-384 declined at the rate of 0.03 with each kilogram per hectare increment of N fertilizer, whereas, SPAD of CP 80-1743 was not affected by the N fertilizer rate (Fig. 6a). The linear SPAD responses of the two water treatments were also affected by N fertilizer rate (Table 4). The SPAD under periodic flooding declined at the rate of 0.03 with each kilogram per hectare increment of N fertilizer and SPAD was not affected by N fertilization under drainage (Fig. 6b). There were no significant three-way interactions involving cultivar, water treatment and N.

Stalk weight

In the data set combined across experiments, stalk weight responded significantly to cultivar, water treatment and N (Table 1). However, all three main effects and the interaction of cultivar × water treatment interacted significantly with the Experiment.

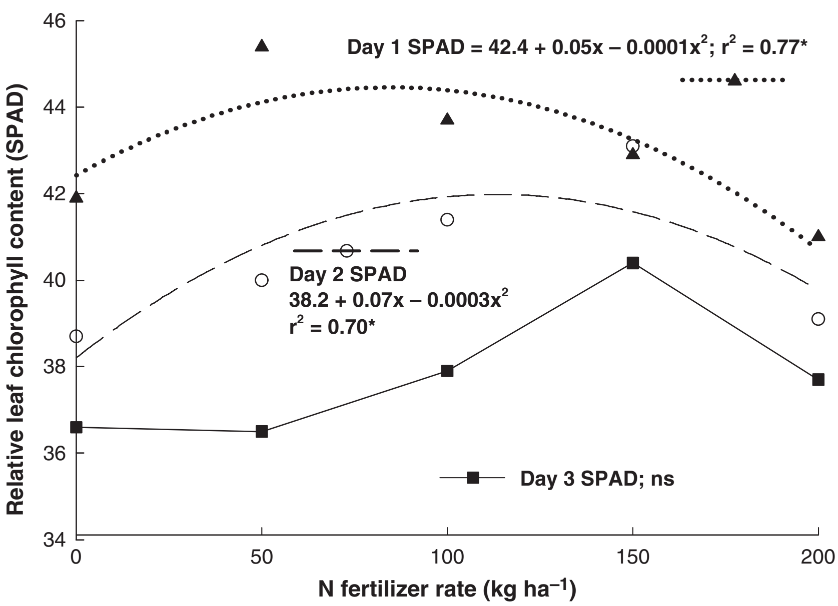

Fig. 4 Responses of relative leaf chlorophyll content (SPAD) to five rates of N fertilizer on three measurement days in Experiment 1.

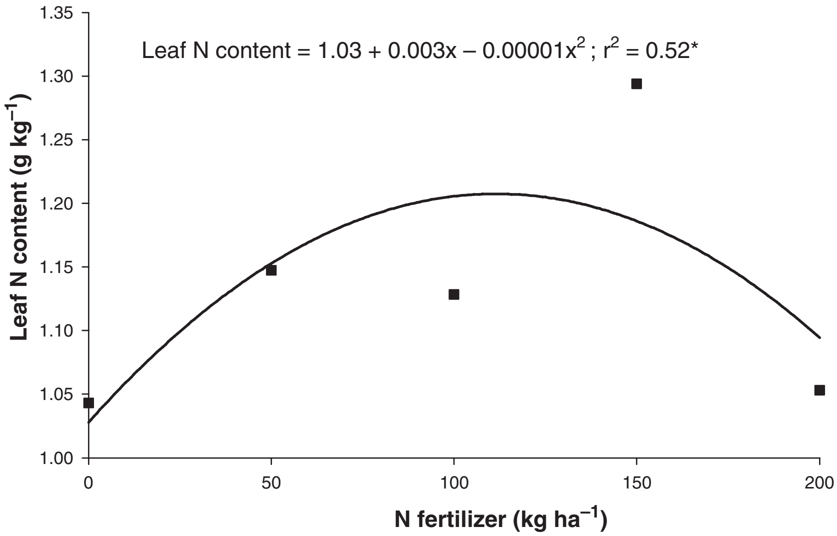

Fig. 5 Response of leaf N content to N fertilizer rate in Experiment 1.

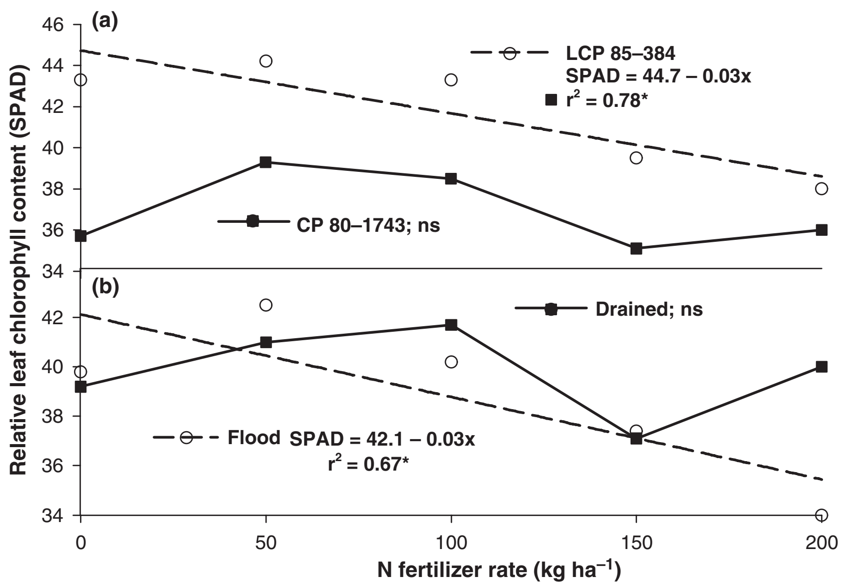

Fig. 6 Responses of relative leaf chlorophyll content (SPAD) to five rates of N fertilizer for two sugarcane cultivars (a) and two water-management treatments (b) in Experiment 2.

In Experiment 1, cultivar differences were significant for stalk weight and cultivar did not interact significantly with any other effect (Table 2). CP 80-1743 had significantly higher stalk weights than LCP 85-384 (Table 3). Stalk weight of the drained treatment was significantly higher than that of the flooded treatment and this difference was not affected by interactions with other effects. These responses of stalk weight to cultivar and water treatment were similar to those obtained for leaf weight in Experiment 1.

In Experiment 2, cultivar, water and the cultivar × water treatment interaction were highly significant (Table 2). For both cultivars, the drained treatments had higher stalk weights than the flooded treatments (Table 3). The significant interaction was probably because of the higher magnitude of the difference between drained and flooded LCP 85-384 stalk weights compared with the difference between drained and flooded CP 80-1743 stalk weights. This suggests that LCP 85-384 was more sensitive to periodic flooding than CP 80-1743 in Experiment 2. These results are similar to those obtained for leaf weight in Experiment 2.

Nitrogen significantly affected stalk weight in each experiment (Table 2). The cultivar × N (linear) interaction was significant in the combined analysis, and it was not significant when 'experiment' was added to the interaction (Table 1). As for leaf weight, the linear stalk-weight response of each cultivar combined across experiments was not significantly affected by N fertilizer rate, but there was a linear trend for LCP 85-384 stalk weights to decline and for CP 80-1743 stalk weights to increase with increasing N fertilizer rates (Fig. 1b). In Experiment 1, the mean stalk weight of both cultivars increased linearly at the rate of 0.06 g for each additional kilogram per hectare of N fertilizer, and in Experiment 2, the response to N fertilizer rate was quadratic for the mean stalk weight of both cultivars, with a maximum predicted stalk weight at the N fertilizer rate of 81 kg ha^{-1} (Table 2 and Fig. 2b).

Stalk weight did not respond significantly to any interactions that included water treatment and N fertilizer rate. These results for stalk weight reinforce other findings in this experiment that supplemental N would be equally beneficial for sugarcane growing on EAA Histosols under water-table depths of 25 cm with or without periodic flooding.

Conclusions

In this pot study of sugarcane exposed to a water-table depth of 25 cm with or without repeated 2-day floods, leaf, root and stalk weights decreased by flooding and often increased by N fertilization up to about 100 kg ha^{-1}. These responses to N were similar for both water treatments suggesting that on EAA Histosols at water-table depths ≤25 cm, N availability is not sufficient during the first few months of sugarcane's growth. CP 80-1743, a sugarcane cultivar that was selected under the high N and shallow water-table depths, common to the EAA, sometimes tolerated the 2-day periodic floods better than LCP 85-384; a cultivar that was selected for sugarcane growers in Louisiana. Results of SPAD measurements suggested that it may be useful for differentiating tolerance of sugarcane genotypes to periodic flooding and results of leaf N content supported those of the SPAD measurements. The information that sugarcane root, leaf and stalk weights increased with up to 100 kg ha^{-1} of N fertilizer encourages follow-up field studies to determine if sugarcane on EAA Histosols with shallow water-table depths and periodic flooding would benefit from supplemental N fertilization.

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